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Advancing Material Appearance Measurement: A Cost-Effective Multispectral Imaging System for Capturing SVBRDF and BTF

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Abstract

This paper introduces a novel system for measuring the appearance of materials by capturing their reflectance represented by Spatially Varying Bidirectional Reflectance Distribution Function (SVBRDF) and Bidirectional Texture Function (BTF). Inspired by goniospectrophotometers, our system uses a fully-aligned and motorized turntable that rotates the sample around three axes to scan the entire hemispherical range of incident-reflection directions. The camera remains fixed while the light source can be rotated around one axis providing the fourth degree of freedom. To ensure high precision color measurement and spectral reproduction for reliable relighting purposes, we use a high-resolution multispectral camera and a broadband LED light source. We provide an overview of our instrument in this paper, and discuss its limitations to be addressed in the future works.

Introduction

The appearance of a product or object is crucial in many fields, including product design and marketing. Visual appearance can impact consumer perception and purchasing decisions, making it a key aspect of product development and branding.

Recent technological advances have led to the creation of materials with unique visual appearances that change based on illumination and observation direction. These materials have been widely applied in various industries, such as architecture, packaging, fashion, automotive, printing, life gadgets, and textile, as they add aesthetic value and improve the user experience.

The Bidirectional Reflectance Distribution Function (BRDF) is a critical parameter for measuring the visual appearance of materials, as it describes how light reflects off a surface in different directions. However, it assumes uniform reflective properties that may not hold true for surfaces with variations in texture or color. Spatially Varying BRDF (SVBRDF) and Bidirectional Texture Functions (BTFs) can address these variations.

Goniospectrophotometers are instruments that measure the BRDF of surfaces, but they are expensive, bulky, and complex, making them inaccessible to many researchers and industries. Moreover, their single-spot measurements limit their application to surfaces with texture and color variations.

While current studies are concentrated on enhancing the precision and effectiveness of image-based systems used to measure SVBRDF and BTF for capturing surface properties with intricate appearance, to our understanding, only a limited number of these systems have been presented in academic circles and accessible in market. Their primary disadvantages include the high cost and maintenance demands, coupled with technological limitations, like the absence of spectral measurement and the failure to cover all the possible illumination and observation angles.

To address these limitations, we developed a new SVBRDF and BTF measurement system that integrates all components into a single device. This system rotates the sample in all directions and uses only one camera and one illumination source, drastically reducing cost. We also use a camera that takes multispectral images in all directions and a LED with better white spectral power distribution to improve color measurement accuracy. This system also provides high and programmable angular steps for both illumination and observation and computes incident and observation directions for each point on the surface separately, unlike similar devices.

Overall, our new measurement system provides a cost-effective and efficient way to measure the visual appearance of materials with complex surface properties, and it has the potential to benefit a range of industries that rely on visual appearance for product development and branding.

Related Works

Measuring appearance is a complex task that involves collecting a large amount of data and conducting extensive data analysis. Therefore, there are not many existing systems proposed for measuring SVBRDF and BTF. Two of the main reflectance measurement system categories are goniospectrophotometers and camera and light source arrays.

Goniospectrophotometers involve one light source and one detector, as well as a sample holder. Typically, either the light source or the detector is fixed while the other rotates with one degree of freedom around the sample holder. The sample holder, which is usually a robotic arm, rotates the sample around three axes. The detector could be a single spot measurement device, used for BRDF measurement, or a CCD/CMOS camera sensor for higher resolution measurement, as is necessary for SVBRDF and BTF measurement of materials with texture and color variations.

Camera and light source arrays consist of several cameras and light sources, which provide faster image acquisition and fewer mechanical movements, leading to less vibration and a simpler electromechanical calibration procedure. In these setups, cameras and illuminations could be mounted on arcs or hemispheres over the sample. For higher angular resolution, the setup may be combined with a rotation stage.

Shwarts et al. [1] reviewed reflectance measurement setups, focusing on BTF measurement systems developed at the University of Bonn in detail. Havran et al. [2, 3] surveyed the state of the art of portable on-site measurement instruments. The same authors proposed a miniaturized SVBRDF- and BTF-represented spatially varying surface reflectance measurement system for on-site applications. This was motivated by previous works, and a hemispherical skeleton gantry with a diameter of approximately 25 cm was designed. The instrument employs 134 LED modules distributed over the hemisphere, and six cameras mounted on an arc that can move along the meridia by a stepper motor. The whole gantry can rotate about the sample surface normal, providing higher angular resolution. The instrument does not have spectral measurement, and replacing cameras and illuminations with spectral ones may increase the cost drastically. Furthermore, due to the large size of spectral cameras, such as filter wheel cameras, replacing cameras with spectral ones may not be feasible in this setup.

Azari et al. [4] proposed a low-cost, programmable setup for BTF acquisition for rendering purposes, which was inspired by goniospectrophotometer setups. It involves a stepper motor-driven sample holder that rotates the sample around three axes, providing three degrees of freedom for BTF measurement. A LED light source moves on a wheel around the sample holder to provide the fourth degree of freedom. Additionally, a conventional RGB camera, Nikon D750 DSLR, is used as a detector in a fixed position. The image registration is also based on an automated algorithm that uses four point markers attached to the corners of the sample holder. Compared to the system presented in this paper, this setup does not employ spectral imaging, and the camera is simply placed on a tripod and not integrated into the device. The sample seems to be off-axis due to mechanical design alignment issues, causing registration problems.

To the best of our knowledge, the only commercially available system on the market for measuring reflectance is the Total Appearance Capture material scanner (TAC7) [5] by X-Rite Incorporated. This system measures the reflectance of samples represented by SVBRDF models. A key feature of TAC7 is its capability in multispectral acquisition. Despite the multispectral imaging technique used in the system presented in this paper, TAC7 utilizes monochrome cameras and eight spectral light sources on three filter wheels with 10 bands. Merzbach et al. [6] used TAC7 to capture surface geometry and multispectral SVBRDF, demonstrating improvements in color accuracy.

Instrument Design

The schematic diagram depicted in Figure 1 provides an overview of the system that has been developed. The primary goal of the system is to capture SVBRF and BTF. Since this is the initial prototype, it has been designed to be modular and adaptable, allowing the camera and illumination to be substituted with alternative technologies. Additionally, the length of the camera and illumination holders can be adjusted to control the distance between the sample and the system. The fundamental components of the system include the camera, illumination, rotational table, control board, and software.

Rotation Mechanism

To achieve all possible combinations of hemispherical incident and reflection directions, four degrees of freedom (DOF) are necessary. In this particular setup, three DOFs are assigned to a motorized turntable, enabling it to rotate about the axes of three stepper motors. The fourth DOF is given to an arm that rotates the light source. In this configuration, the camera is fixed on the camera holder, and the intersection point of the optical axis of the camera and the axes of all four motors is located at the center of the table surface, referred to as the zero point. The surface of the table can be adjusted to accommodate samples with varying thicknesses without affecting the rotation axis.

Three coordinate systems are defined in this setup. The first is the device coordinate system, which is determined by the axes of motors one to three and is not an Euclidean space. The second

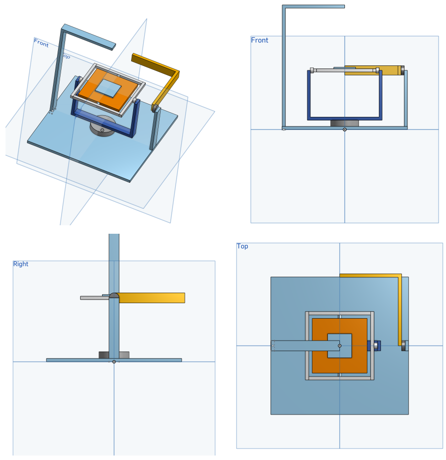

Figure 1. Overview of mechanical design of the proposed system. From top-left to bottom-right: an arbitrary, front, right, and top views.

is the sample coordinate system, which is considered as an Euclidean space with the origin positioned at the zero point above the table. This coordinate system moves with the rotations of the motors and is therefore referred to as the moving coordinate system. The third is a fixed coordinate system in the room, known as the world or lab coordinate system. Rotations about the sample and world coordinate axes are referred to as intrinsic and extrinsic rotations, respectively. Additionally, a zero position is defined as a point where all the coordinate systems coincide, and the absolute rotations are counted from that point. Four motors enable rotation of the sample holder: M1 for rotation around the $\boldsymbol{x}$-axis, M2 for rotation around the $\boldsymbol{y}$-axis when the holder is at zero position, and M3 for rotation around the Z-axis. M4 rotates the light source around the Y-axis.

Light Source

The light source assembly comprises a mounted LED, collimator, controller, and power supply. A single LED with a white spectrum is affixed to the end of a heat sink, with an adjustable collimator positioned in front of the LED. The LED emits a cold white light with a Correlated Color Temperature of 6500 K and a typical output power of 1430 mW. The intensity of the LED is regulated by a constant current LED driver with a USB 2.0 interface. Furthermore, a power supply with a 12 V and 1 A output powers the driver and provides the necessary power for the LED. The spectrum of the light source is depicted in Figure 2.

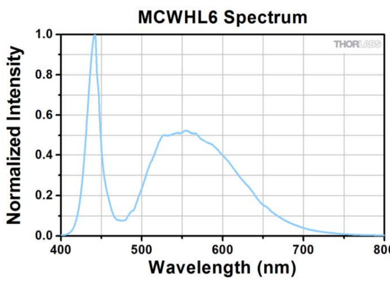

Figure 2. The spectrum of LED. [7]

Camera

The SpectroCam multispectral wheel camera [8] serves as the detector in this image-based system. The camera features a CCD silicon panochromatic sensor with spectral responsivity ranging from 400nm to 1000nm, and it is equipped with a filter wheel containing 8 filters in front of the sensor. However, only six filters in the visible range (as seen in Figure 3) are used due to the spectral limit of the light source in the UV and IR regions. The camera images possess a spatial resolution of 2456 x 2058 pixels, with a pixel pitch of 3.45μm. The digital output of the camera is capable of achieving a maximum of 12 bits, which is communicated through a Gig-E standard. The sensor's original low dynamic range, which covers only 2.5 orders of magnitude, is insufficient for a variety of materials. Therefore, a multispectral HDR imaging method is used through bracketing.[9]

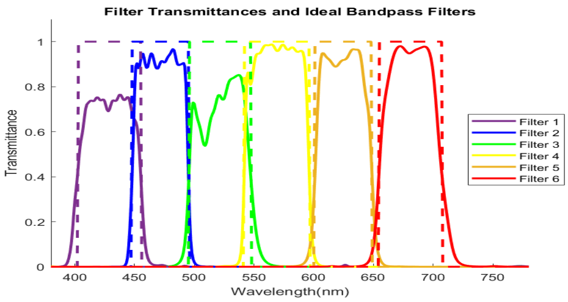

Figure 3. *Multispectral camera filter transmittances.*

Control System

The main electronic board used in the system is the TinyG multi-axis motion control system [10], which controls and drives four stepper motors as well as homing and kill-machine light barrier switches. This board is specifically designed for precision motion control applications like CNC machining. It contains an Atmel ATxmega embedded microcontroller and four TI DRV8818 stepper motor drivers. The microcontroller receives G-code commands through a USB connection and interprets them locally. The stepper drivers are capable of providing microstepping up to 1/8 for smoother and higher angular resolution rotations. The drivers can handle up to 2.5 Amps current per winding, making them suitable for controlling both small and larger stepper motors such as motor 4 using the same board.

To synchronize all the components in the system, a software written in C++ is used which integrates SDKs of the light source, camera, and TinyG. The software uses a serial library for USB communication, OpenCV for image processing, and the Qt library for GUI implementation.

Instrument Realization

The device implementation is presented in Figure 4. The coordinate system consists of XYZ for the lab coordinate and ***xyz*** for the sample coordinate. The origin of the sample coordinate is set at the device's zero point, where all components are assembled and aligned such that the optical axis of the camera, illumination, and motor axes intersect.

During initialization, each motor is rotated sequentially until it reaches the corresponding light barrier switch, a process called homing. Homing accurately brings the machine to a fixed position. After homing, each motor moves to a bias angle to reach the zero position, where the sample, lab, and instrument coordinates are all identical, and the illumination and camera directions align with the Z-axis. Absolute angles are then calculated from this point. Protractors are installed on each motor axis for the visually inspection of the motor rotations.

Moreover, a live video of the camera output is displayed in the software's adjustment mode, with a crosshair on the window aiding the adjustment of the camera and illumination by using the appropriate screw adjusters on the camera and illumination holders.

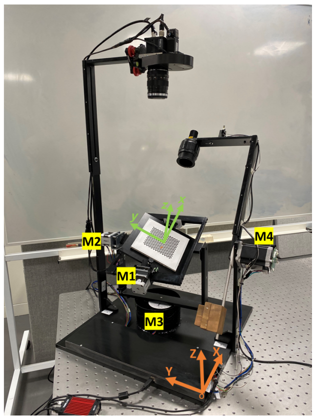

Figure 4. *This figure depicts the device's configuration, with the sample and lab coordinates indicated in green and orange, respectively.*

Spherical to Motors Coordinate Conversion

In BRDF measurement, the incident and reflection directions are given in spherical angles in the sample coordinate space. The zenith and azimuth angles of the incident direction are represented by θ_i and ϕ_i, respectively. Similarly, the reflection direction is defined by θ_r and ϕ_r in the spherical coordinate system. However, the instrument's control system receives the rotation angles of each motor to reach the desired position, which requires the conversion of spherical incident and reflection directions into motor rotation angles. To achieve this, the rotation angles of motors M1, M2, M3, and M4 are represented by A, B, C, and D, respectively. The following equations are used to convert the spherical angles into motor rotation angles:

$$A = \text{atan2}(\sin(\phi_r)\cdot\sin(\theta_r), \cos(\theta_r)) \quad (1)$$

$$B = \sin^{-1}(-\cos(\phi_r)\cdot\sin(\theta_r)) \quad (2)$$

$$\begin{aligned} C = \text{atan2}(&\sin(\theta_r)\cdot\sin(\phi_r)\cdot\cos(\theta_i) \\ &-\sin(\theta_i)\cdot\sin(\phi_i)\cdot\cos(\theta_r), \\ &\cos(\theta_r)\cdot(\sin(\theta_i)\cdot\cos(\phi_i)\cdot\cos(\theta_r) \\ &-\sin(\theta_r)\cdot\cos(\phi_r)\cdot\cos(\theta_i)) \\ &+\sin(\theta_i)\cdot\sin(\phi_r)\cdot\sin^2(\theta_r)\cdot\sin(\phi_r-\phi_i)) \end{aligned} \quad (3)$$

$$\begin{aligned} D = \cos^{-1}(&\sin(\theta_r)\cdot\sin(\theta_i)\cdot\cos(\phi_r-\phi_i) \\ &+\cos(\theta_r)\cdot\cos(\theta_i)) \end{aligned} \quad (4)$$

Image Registration

The proposed setup for angular image acquisitions relies on mechanical movements, and unlike stationary setups that use a few markers or borders, this setup requires a proper image registration procedure. This procedure includes camera calibration to calculate intrinsic and extrinsic camera parameters through the camera matrix, as well as image rectification and registration through the homography matrix. In the developed software, image registration is considered a post-processing procedure that occurs after image acquisition is complete. The entire post-processing process begins with camera calibration and image distortion correction, then proceeds with homography matrix calculation and image warping. The output images for all combinations of incident and reflection directions are registered images that appear to have been captured from a perpendicular viewing angle.

Camera Calibration

Camera calibration is a crucial process that involves estimating both intrinsic and extrinsic parameters of a camera which maps information from a 3D world into a 2D image. Intrinsic parameters describe the camera's internal behavior, including lens distortions, sensor pixel size, and focal length, while extrinsic parameters describe the camera's position and orientation in 3D space. Calibrating a camera is essential for correcting distortions and other factors that can impact the acquired image, which is necessary for obtaining accurate and reliable information about the sample.

In this setup, camera calibration is performed using a ChArUco board in conjunction with the OpenCV library[11]. The ChArUco board is a type of checkerboard pattern that combines a traditional black and white chessboard with ArUco markers. The ChArUco pattern has several advantages over other types of calibration boards, such as providing higher precision corner detection and working well even when parts of the board are occluded in the image. A 10 by 10 square board with a 1cm square side and a dictionary of 6 by 6 with a total of 250 marker IDs is used in this application. Although each ArUco marker has a unique ID and can be correctly identified by the algorithm regardless of its rotation, the top left square is marked, and a circle is drawn in the center of the board as a crosshair for visual inspection purposes.

Image Rectification and Registration

Using a ChArUco board for camera calibration can also be useful in image rectification and registration, eliminating the need for multiple boards and different marker types for various tasks. The captured images in the measurement phase are first corrected for distortions using the camera matrix. Then, the board's corners are detected in each image, and the corresponding points are identified by considering each image as the source image and the original ChArUco board as the fixed image in registration. Image registration involves transforming the captured images (source) to align with the original ChArUco board image (fixed).

Since ChArUco can be detected by the algorithm even if it is partially occluded in the images, it can be used for capturing images of samples. For samples with a diameter of 5 cm, only some markers may be occluded, but this does not significantly affect the precision of the algorithm. The high precision of corner detection with a ChArUco board in different viewing angles provides sufficient accuracy for identifying corresponding points in different images and calculating a reliable homography matrix. Additionally, each marker on the board has a unique ID, which helps the algorithm avoid errors when finding corresponding points in different viewing angles.

Example Sample Measurement

After assembling all the components of the device, an experiment was conducted to test the calibration, image capture, and post-processing procedures using a mini colorchecker, which measures approximately 4 cm by 3.5 cm and is placed at the center of the sample holder. Due to the large number of images generated, only a few images captured under the same incident direction but with different reflection directions and of the fourth spectral band are presented in Figure 5. These images are fed into the post-processing stage for rectification and registration. Figure 6 shows the post-processing output images, which demonstrate a high level of precision in image registration.

However, there are two limitations to the device that must be addressed. Firstly, the equations used to convert spherical to motor coordinates map incident and reflection directions to motor rotation angles in a way that limits the light source arm angles to the range of 0 to +180 degrees, whereas the device can only rotate the light source in the range of -120 to +120 degrees due to mechanical constraints. Consequently, the current configuration and conversion equations prevent the device from scanning about 5 percent of all possible incident and reflection combinations.

Secondly, in situations where the angle between the light source and the camera is less than 5 degrees, depending on the sample size, the light source obstructs the camera input, making it impossible to capture the image.

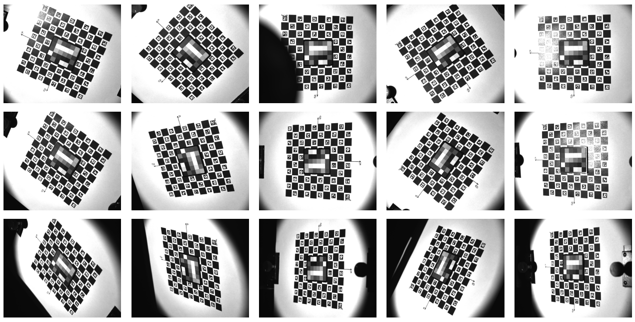

Figure 5. *Captured images. The incident light is fixed at theta=20 and phi=0, while the reflection direction changes. The images are arranged in rows that correspond to different angles of reflection (theta = 15, 30, and 50 from top to bottom) and in columns that correspond to different directions of reflection (phi = -120, -60, 0, 90, and 180 from left to right).*

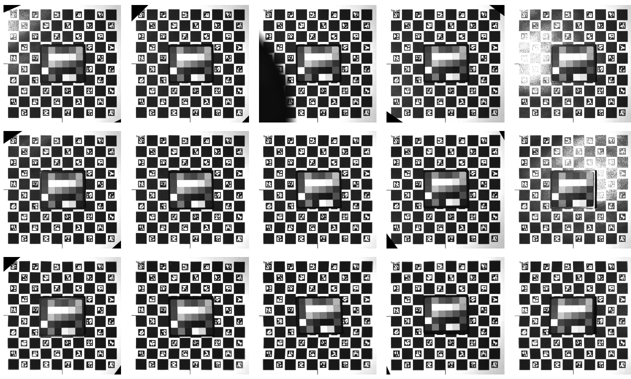

Figure 6. *Registered images as output of post-processing stage. The imaging geometries are the same as in Figure 5.*

Conclusion

In conclusion, we have presented a novel system for measuring the appearance of materials through the capture of their reflectance using Spatially Varying Bidirectional Reflectance Distribution Function (SVBRDF) and Bidirectional Texture Function (BTF). Our system is inspired by goniospectrophotometers and uses a fully-aligned and motorized turntable to scan the entire hemispherical range of incident-reflection directions, while using a high-resolution multispectral camera and a broadband LED light source to ensure high precision color measurement and spectral reproduction.

Our system addresses the limitations of existing SVBRDF and BTF measurement systems by providing a cost-effective and efficient way to measure the visual appearance of materials with complex surface properties. It has the potential to benefit a range of industries that rely on visual appearance for product development and branding.

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Markus Barbieri is co-owner of Barbieri Electronic, Italy. As CTO he develops specialized and unique color measurement solutions for large format, wide format, flatbed and industrial printing. He is author of two patents. Professional Activities: He is delegate Barbieri electronic at the International Color Consortium (ICC), member of the technical committee of the Fogra Digital Printing Working Group and delegate of Barbieri electronic at UNI/CT 042/SC 01/GL 15 "Tecnologia grafica"

Gaël Obein is doctor in Metrology and associate professor at National Conservatory of Arts and Crafts (FR). He received his PhD in 2003 with a thesis entitled : "Metrology of gloss, physical and psychophysical approach". Today he is head of LNE-CNAM, the French Designated Institute for Temperature, Length, Photometry and Radiometry. His research interests are the measurement of BRDF, BSSRDF and the link between these quantities and the visual perception of surfaces.

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